TANTALUM HOT-ELECTRON BOLOMETERS FOR LOW-NOISE HETERODYNE RECEIVERS

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ABSTRACT

We describe superconducting diffusion-cooled hot-electron bolometers that were fabricated from tantalum films grown on a thin niobium seed layer. The seed layer promotes single-phase growth of the Ta films, resulting in high-quality bolometers with transition temperatures up to 2.35 K and transition widths of less than 0.2 K. An S-parameter measurement set-up in a He-3 cryostat was used to measure device impedance versus frequency of a 400 nm long device at a temperature of 400 mK. It is shown that a 3 dB roll-off frequency of about 1 GHz can be achieved when the device resistance matches the impedance of the embedding network (no electrothermal feedback). This would lead to a prediction of 16 GHz for a 100 nm device, and indicates that a heterodyne mixer using a Ta HEB should be able to operate at several GHz even with a significant amount of electrothermal feedback.

INTRODUCTION

Superconducting hot-electron bolometer (HEB) mixers that are currently under development for observational platforms such as *Herschel* and *SOFIA* use either diffusion-cooled niobium devices with transition temperatures (T_C) of 5 to 7 K, or phonon-cooled niobium nitride devices with even higher T_C (an overview can be found in the references[1]). Since theory predicts that the mixer input noise should be proportional to T_C when an HEB mixer is limited by thermal fluctuation noise [2], it is of interest to study materials with lower-temperature transitions. A noise reduction of a factor of two can in some applications lead to a fourfold increase in data gathering capacity. The local oscillator (LO) power requirement is proportional to T_C^2, and can therefore also be reduced, which is advantageous at frequencies above 1 THz where solid-state sources are at present too weak for many applications. These advantages naturally have to be weighed against potential system disadvantages of the lower T_C, such as the increased complexity of cryogenic coolers and potential saturation effects in the mixer element itself. Only a few lower T_C mixers have been studied previously, such as niobium devices where the transition temperature has been suppressed by an external magnetic field [3], or by the proximity effect from thin gold coatings [3,4]. The predicted dependencies of noise temperature and LO power on transition temperature have been confirmed at microwave frequencies [3]. Aluminum-based bolometers ($T_C \leq 2K$) have also been investigated [5,6], but found to be unsuitable for THz mixers for a variety of reasons.

A superconductive material with a naturally lower T_C offers practical advantages compared to the use of magnetic fields and bi-layers. Here we investigate the usefulness of tantalum (Ta) for low-noise diffusion-cooled HEB mixers. Ta has superconducting properties that are similar to those of Nb, except for the T_C which is about a factor of 2 lower (for thin films: $T_C \approx 3K$ for Ta, versus 6-7K for Nb). Thus Ta should be a predictable material with the desired properties. Tantalum does however add some fabrication challenges, since it forms thin films that contain two lattice phases. This would be unacceptable for a practical device, since the additional electron scattering at the grain boundaries would tend to suppress the diffusion-cooling mechanism, and also because the different transition temperatures of the two phases leads to a broadening of the transition. The ultimate goals of this study can therefore be defined as:

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1) To demonstrate that high quality devices can be fabricated, with T_C between 2 and 3 K and transition widths (∂T_C) similar to niobium devices (0.1 to 0.2 K).
2) To verify that the diffusion-cooling mechanism is sufficient to produce intermediate frequency (IF) bandwidths that are useful in a typical receiver application (at least a few GHz).
3) To demonstrate that the mixer noise can be lower than for higher-T_C materials.
In this paper we will address the first two of these points, by describing the DC and microwave properties of our fabricated devices.

DEVICES

Based on previous experience, HEB devices with resistance values between about 20Ω to 100 Ω can be easily matched to microwave coupling structures, and provide the best mixer performance. For Ta, this can be achieved with microbridge lengths of 100–400 nm, widths of 100-200 nm and a film thickness of 10 nm. Our devices were fabricated on a silicon wafer by sputter deposition of a 10 nm Ta film on top of a 1.5 nm Nb seed layer. The purpose of the seed layer is to promote growth of the desired tantalum alpha-phase, giving higher superconducting transition temperatures and sharper transitions [7]. Thick gold pads serve to define the length of the microbridge and to prevent Andreev reflections from trapping heat in the device. We have utilized a modified version of our self-aligned processing method previously developed for Nb HEB devices [8] and found that it works well for Ta. The main modification is the use of SiO instead of Au as an etch mask, which improves the device definition and eliminates the need to remove the mask from the finished device.

The devices have transition temperatures of up to 2.35 K, a typical resistance-versus-temperature (R vs. T) curve is shown Fig 1. This device is 0.4 microns long and 0.2 microns wide, with a normal state resistance of about 80 Ω and a transition at 2.25 K. The R vs. T curve has a "foot" structure that is associated with the regions at the two ends of the device, similar to that seen in niobium bolometers. The curve clearly shows that the transition width of this device is similar to that of a niobium device, so that bolometric mixers with similar properties should be feasible.

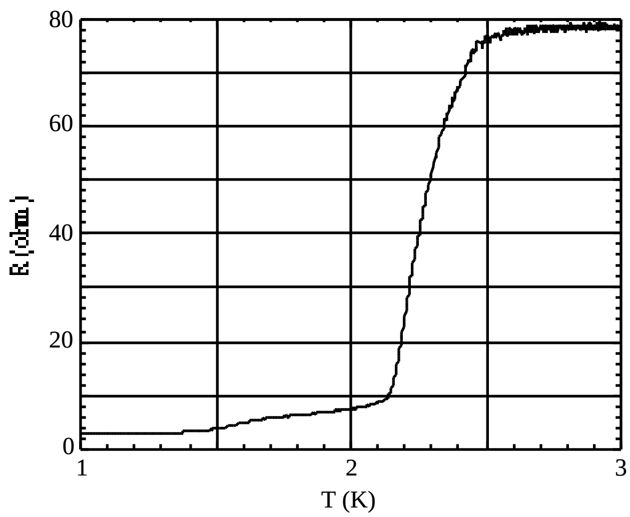

Figure 1: *R vs. T curve for the 400 nm long device that was used in the microwave measurements.*

IMPEDANCE MEASUREMENTS

To determine the thermal response time of tantalum HEB's, a He-3 cryostat was fitted with electronics for conducting microwave reflection measurements of the device, see Fig. 2. The set-up allows measurements at frequencies between about 200 MHz and 15 GHz, at temperatures down to 380 mK. This allows a more direct measurement of the device speed than for example a mixer bandwidth measurement, which is affected by input and output coupling variations with frequency. In the low-frequency limit the bolometer should have the same properties as at DC, and the device impedance should be equal to the differential resistance dV/dI at the bias point. At frequencies that significantly exceed the response roll-off frequency (but that are lower than the gap frequency of the superconductor) the device impedance should be the DC resistance V/I. A cross-over between these cases occurs near the roll-off frequency that is set by the thermal time constant at the DC bias point. An expression for the impedance as a function of frequency can be derived from a simplified lumped thermal model, where the device is represented by the electronic heat capacitance c_e that is heat sunk to the thermal reservoir by a heat conductance G :

$$Z(f) = R_0 \; \frac{1 + C + j \;\; 2\pi f \tau_0}{1 - C + j \;\; 2\pi f \tau_0} \qquad (1)$$

where R_0 is the resistance at the DC bias point, $\tau_0 = c_e/G$ is the thermal relaxation time of the device (excluding electrothermal feedback), and $C = I_0^2 \; (dR/dT)/G$ is the self-heating parameter at DC bias current I_0.

The device impedance as a function of frequency was measured for the three DC bias points that are marked on the IV curve in Figure 3. In order to estimate the device speed, equation 1 can be fitted to the data by adjusting τ_0 and C. The resulting thermal speed $f_0 = 1/(2\pi\tau_0)$ for the three points are 750 MHz, 1.13 GHz and 2.0 GHz. A possible reason that these numbers are not identical to each other is that the "lumped element" thermal model used is too simplistic to accurately describe this relatively wide thermal bias range of this distributed-temperature device. In addition to the measured curves, Figure 4 also shows the fitted curve for point B. Since bias points A and B best represent the device under realistic operating conditions as a mixer, a reasonable estimate of the speed for this 400 nm long device would be about 1 GHz.

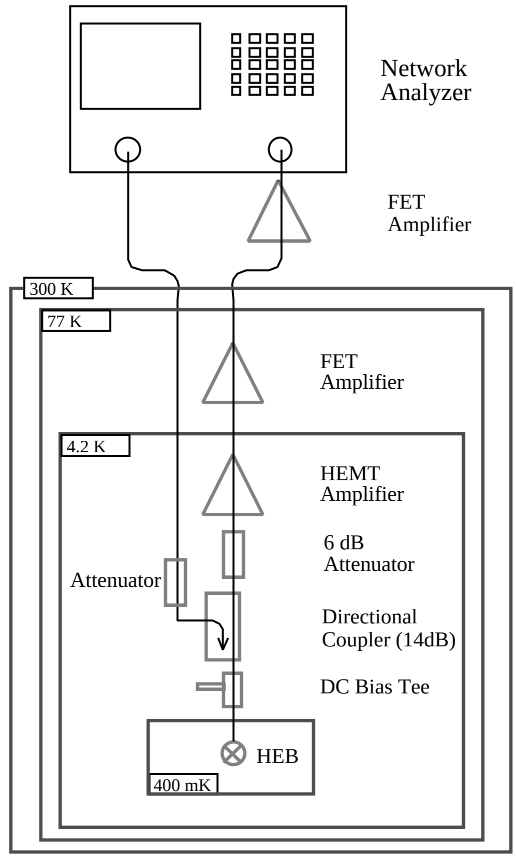

Figure 2: *Schematic of the impedance measurement setup. A helium-3 cryostat supplied by Infrared Laboratories is used to cool the Ta HEB to a temperature of 400 mK.*

CONCLUSIONS

Submicron-sized tantalum HEB devices with the desired transition temperatures and transition sharpness can indeed be fabricated using the niobium seed-layer technique. The sheet resistance is low enough to make devices that can be matched to antennas and other microwave coupling structures. The measured 400 nm long device can be expected to have a 3 dB mixer conversion efficiency roll-off at about 1 GHz, excluding electrothermal feedback. Due to the relatively small end effects (the "foot" structure in the R vs. T curve), it should be possible to use devices that are as least as short as 100 nm. Since the thermal relaxation time is proportional to the square of the device length [9,10] (diffusion-cooling), these would then have a "raw" speed of about 16 GHz. Since only a few GHz of bandwidth is needed for most mixer applications, this would indicate that Ta HEB devices will be fast enough even when including the slowing effects of electrothermal feed-back present in most bolometer mixer circuits.

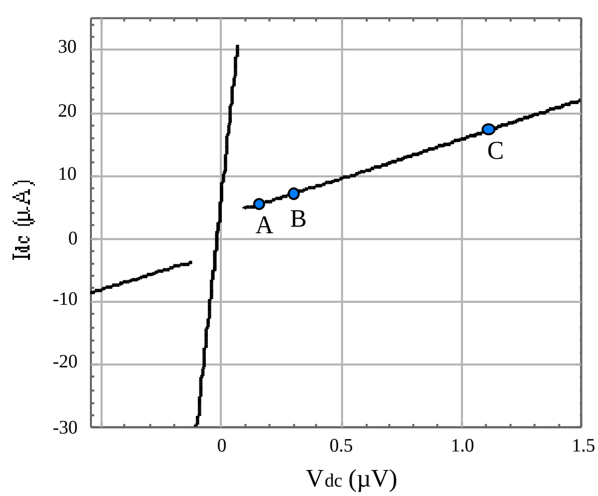

Figure 3: *Current-versus-Voltage characteristic for a 400 nm long device as measured at 400 mK. The three markers (A, B, C) indicate the bias points that were used in the device impedance measurements.*

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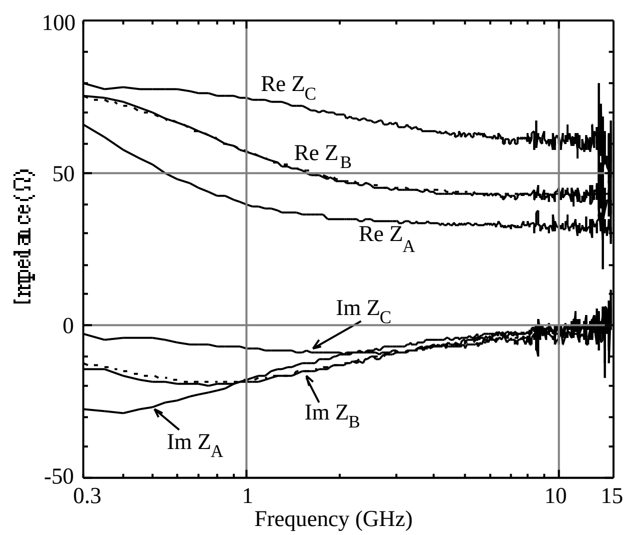

Figure 4: *Measured impedances (Z_A, Z_B, Z_C) curves for the three bias points in Figure 3. Also shown is a fitted theoretical curve for bias point B (dotted).*